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Larger soil amplification for stronger ground motion from SMART-1 records

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ABSTRACT: Records obtained in the strong motion array SMART-1 in Taiwan have been used to study the effect of soils for different earthquakes. A number of events having similar azimuth with respect to the array and various magnitudes and epicentral distances have been selected and spectral analysis has been carried out with their corresponding records. The influence on the soil response of different earthquake parameters such as magnitude and distance has been investigated. Analysis of the soil/rock amplification ratios computed from the selected set of accelerograms shows a clear dependence of these ratios, in the low frequency bands, on the "input" ground motion on rock. The soil amplification is greater for higher input levels, suggesting significant non-linear behaviour of the soils. For the frequency band from 0.3 to 0.6 Hz and for mean values of undamped pseudo-displacement (PSD) on the rock site less than 0.4 cm (shear strain $\approx 10^{-3}$%) the soil amplification factor is around 2 while for rock PSD larger than 1 cm (shear strain $\approx 10^{-1}$% to 10^{-2}%) this amplification factor can be larger than 6.

1 INTRODUCTION

In spite of the increasing number of strong motion records now available, not many of them are suitable for a detailed analysis of soil effects. A few dense accelerometer arrays have been installed in different regions around the world. Records obtained in these arrays can give more appropiate information leading to a better characterization of the soil response to weak and strong earthquake motions.

The SMART-1 accelerometer array is located in the northeast corner of Taiwan near the city of Lotung in the Lanyang plain (Bolt et al., 1982). Due to the high seismicity level of the area an important set of strong motion records corresponding to earthquakes with different characteristics located at a broad range of distances to the array have been obtained since 1980.

In this research, a selected set of earthquakes recorded on the SMART-1 array has been used to analyze the effect of soil amplification on the recorded ground motion and its dependence on different parameters.

2 DATA FROM SMART-1 ACCELEROGRAPH ARRAY

Records obtained in the SMART-1 array contain highly valuable information on soil response. The array consists of 39 force-balanced triaxial accelerometers with digital recording, distributed as shown in Fig. 1: one at the center of the site (station C-00); thirty six instruments evenly spaced distributed on three concentric circles of radii 200 m (inner ring, I), 1000 m (middle ring, M) and 2000 m (outer ring, O), at a rate of 12 accelerometers per circle; and two additional stations (E-01 and E-02) added to enlarge the array to the South edge of the Lanyang plain where rock outcrops are exposed (Bolt et al., 1982; Abrahamson et al., 1987).

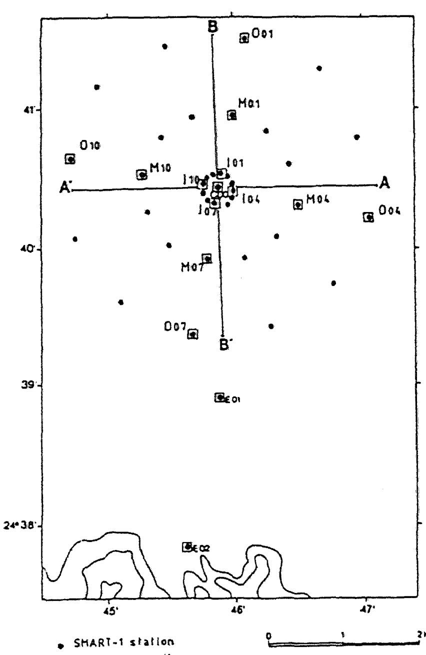

Figure 1. Distribution of accelerometers in SMART-1 array. Only the stations considered in this study are labeled.

All the instruments are located on soil sites, in a recent alluvial plain except for the station E-02 that is located on rock, on a slate outcrop. The water table in all this area is at or near the ground surface. Fig. 2 shows two sections (EW and NS) of the velocity structure across the array. The soils beneath the array consist of 3-18 meters of grey sandy silt and silty sand with some gravel over recent alluvium down to 30-60m. This layer overlies a 170-540 m thick deposit of Pleistocene gravels thining from northeast toward southwest. The basement consists of Miocene Lushan Formation slate (Wen and Yeh, 1984).

For our study only stations from a cross configuration sub-array (Fig. 1) have been considered, namely stations E-01, O-07, M-07, I-07, C-00, I-01, M-01 and O-01 (SN arm) and stations O-10, M-10, I-10, C-00, I-04, M-04 and O-04 (WE arm). In addition the rock site station E-02 has been taken as a common reference for all events. All these stations are marked with a different symbol in Fig. 1.

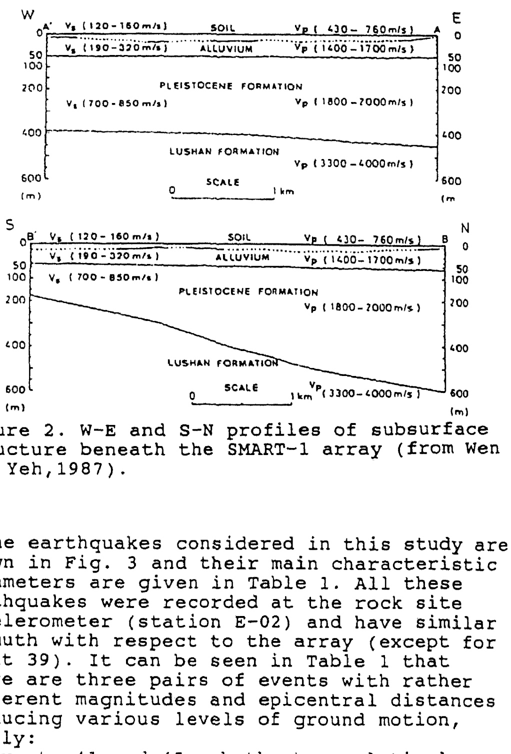

Figure 2. W-E and S-N profiles of subsurface structure beneath the SMART-1 array (from Wen and Yeh,1987).

The earthquakes considered in this study are shown in Fig. 3 and their main characteristic parameters are given in Table 1. All these earthquakes were recorded at the rock site accelerometer (station E-02) and have similar azimuth with respect to the array (except for event 39). It can be seen in Table 1 that there are three pairs of events with rather different magnitudes and epicentral distances producing various levels of ground motion, namely:

-Events 41 and 45 , both at a relatively large distance (70-80 km) with local magnitudes 6.2 and 7.0, respectively; the last one is the event with largest magnitude recorded at the array and caused considerable damage in northern Taiwan.

-Events 34 and 37 (M_L= 5.8 and 5.3), located at an intermediate distance of about 30-35 km from the array.

-Events 43 and 44 both at a same location very near to the array site, although the magnitudes are very different (6.2 for event 43 vs. 4.9 for event 44).

Another earthquake (event 39) has also been considered in this study because of the high accelerations recorded in the array (greater than 0.33g).

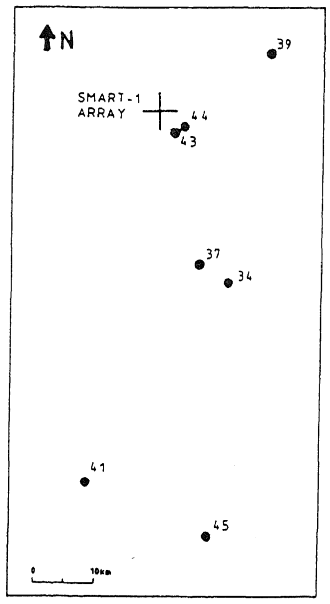

Figure 3. Location of the events considered in this study (see table 1).

EVENT	Date	ML	Δ (km)	h (km)
34	85.08.05	5,8	34	1
37	85.10.26	5,3	30	2
39	86.01.16	6,5	22	10
41	86.05.20	6,2	71	22
43	86.07.30	6,2	6	2
44	86.07.30	4,9	5	2
45	86.11.14	7,0	79	7

Table 1. Parameters of the events considered in this study.

3 SOIL AMPLIFICATION

For all events listed in Table 1, the response spectra of the horizontal component records have been computed. As SMART-1 accelerograms are recorded in the field in digital form by identical instruments they are not affected by the digitization process or instrumental response variability and there is no need for many of the corrections inherent in processing analog records. For each individual accelerogram obtained in every station of the subarray, pseudovelocity response spectrum (PSV) for 0% damping (closely related to the envelope of Fourier acceleration spectrum) has been calculated and the spectral ratio with respect to the rock site obtained.

Examples of undamped PSV response spectra of the East component for events 37 and 43 recorded on rock and soil sites are shown in figures 4 and 5. The spectra corresponding to stations in SN and WE profiles (the two lines of the cross subarray) are presented together with the rock site spectrum. Low frequency noise appears in these records for frequencies smaller than 0.3 Hz. For higher frequencies no

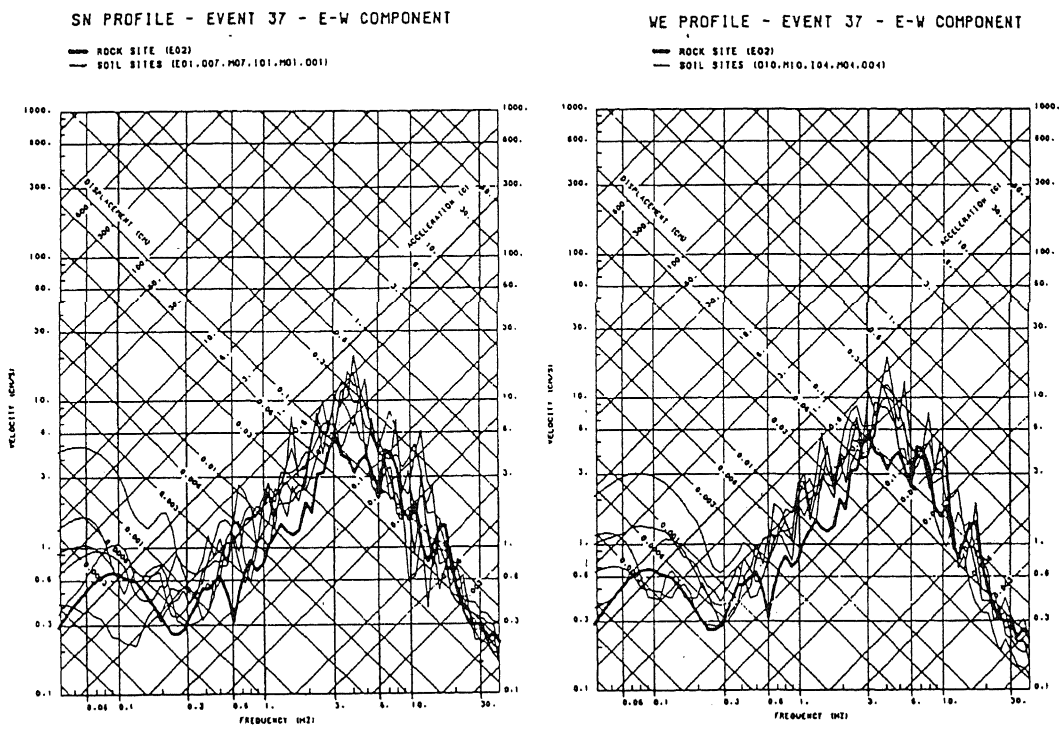

Figure 4. PSV response spectra (0% damping) for rock and soil sites. E-W component. Stations corresponding to SN and WE profiles. Event 37.

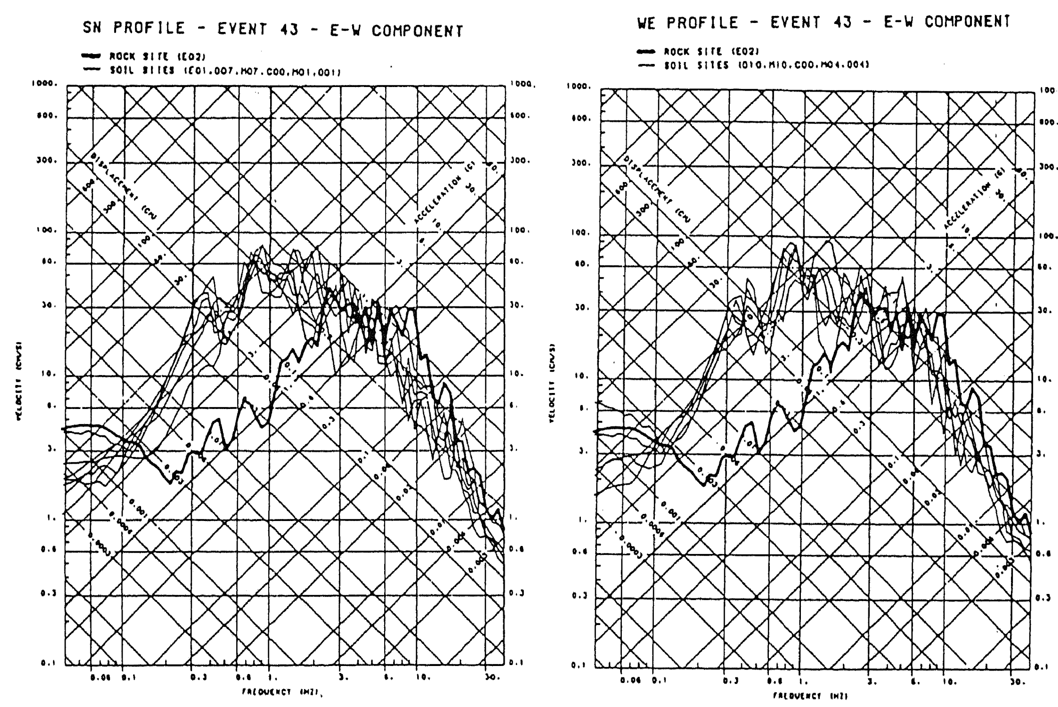

Figure 5. PSV response spectra (0% damping) for rock and soil sites. E-W componet. Stations corresponding to SN and WE profiles. Event 43.

filtering has been applied to the signal. A clear amplification in the soil for low frequencies (up to about 3 Hz for event 43 and to 6 Hz for event 37) is observed, whereas in the high-frequency range, the differences in the spectra for rock and soil sites are much smaller. Because there is not significant reduction in the soil site spectra for high frequencies it is concluded that differences in peak ground acceleration recorded on rock and in soil are of second order compared with the amplification effect in the low frequencies and, consequently, with the differences in ground displacement.

This effect of amplification of ground motion at soil sites for low frequencies is observed in all the events studied. Soil ground motion reduction for high frequencies is a smaller effect and is not always present. As has been pointed out by Caillot and Bard (1990) in some cases peak accelerations in E-02 station (rock site) may be lower than in some soil sites. This may be related to the characteristics of the rock at the site which, as it is shown in Fig. 2, has a low value for the P-wave propagation velocity.

A slightly larger variability in the spectra of soil stations in the SN profile with respect to those in the WE profile is observed for all the earthquakes considered (Figs. 4 and 5). This may be related to the variation of sediment thickness from North to South compared with an almost constant thickness in the East-West direction.

4 SOIL AMPLIFICATION DEPENDENCE ON INPUT LEVEL

A large difference in the soil/rock amplification factors from event 37 to event 43 is observed in figures 4 and 5. Event 43, a very close earthquake with magnitude 6.2, shows greater amplification than event 37, a lower magnitude (5.3) and more distant earthquake.

The recorded accelerograms and calculated displacement records for East-West components of event 37 on rock (E-02) and soil (M-07 and I-01) sites are shown in Fig. 6. The peaks of ground acceleration in soil are only a 10% greater than the corresponding value on rock while the amplification of peak ground displacements by the soil layers reaches a factor of 1.7. Acceleration and displacement records on rock and soil sites for event 43 are shown in Fig. 7. In this case the peak accelerations on soil are reduced by a maximum factor of about 0.6 while the peak ground displacement is more than 7 times larger than the corresponding value on rock. The large long period displacements that appear on the time histories for soil sites are a direct consequence of the amplification effect which is stronger in the 0.3-1 Hz frequency band as seen in Fig. 5.

After a careful analysis of the possible causes of the big differences observed in the amplification factors, it is conjectured that such behaviour depends only on the spectral input level recorded on bedrock.

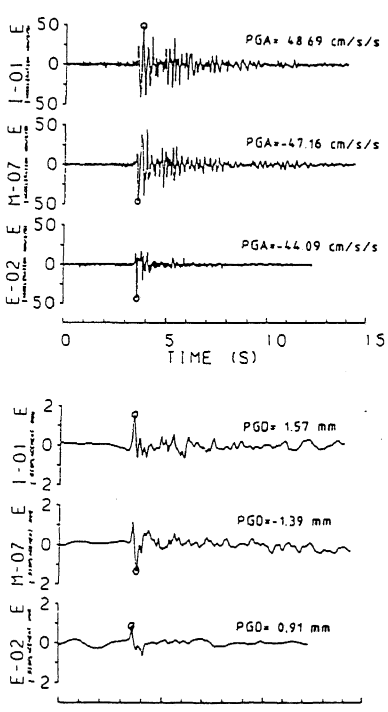

Figure 6. Corrected acceleration and displacement records for rock (E-02) and soil sites (M-07 and I-01). Event 37, EW component.

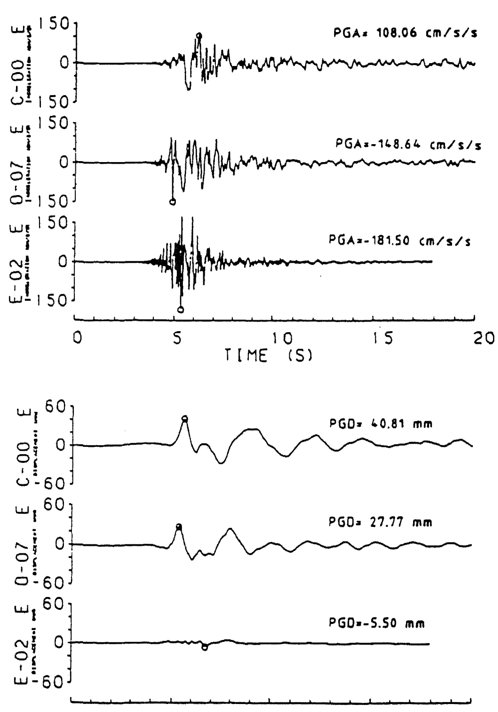

Figure 7. Corrected acceleration and displacement records for rock (E-02) and soil sites (o-07 and c-00). Event 43, EW component.

This dependence of soil amplification factor on input level has been investigated for all the events listed in Table 1. In figure 8, mean soil/rock spectral ratios are plotted versus values of pseudo-displacement (PSD) on the rock site, for the frequency band 0.3-0.6 Hz. The x-values in Fig. 8 are the values of PSD spectra (0% damping) on rock averaged within this frequency band. The y-axis values are calculated by averaging soil/rock spectral ratios for the different stations.

In figure 8 two sets of data points can be distinguished. The first one with lower input levels (rock site PSD less than 0.4 cm) *correspond to events 34, 37, 41 and 44, i.e.* includes close earthquakes of small magnitude and distant ones of larger magnitude. The second set, with higher rock PSD levels corresponds to events 39, 43 and 45, including close and distant large magnitude events.

Within this 0.3-0.6 Hz frequency band, the amplification factor for the first set of data points (i.e. corresponding to lower input levels) is around 2 while for the second set (i.e. corresponding to higher input levels) amplification is stronger, reaching a factor of 8. This dependence of amplification factors on the input motion level at the bedrock is also present for higher frequencies up to about 1 Hz.

An explanation of this nonlinear behaviour can be searched in the geotechnical properties of the very soft sediments beneath the SMART-1 array. The results of laboratory testing for these soils (Anderson and Tang, 1987) indicate that the shear modulus and damping become nonlinear at shears strains of about 10^{-2}% (Figure 9).

A rough estimation of the shear strain levels, γ , involved in the earthquake ground motions considered in this paper can be obtained from $\gamma = \Delta u/u$, where u and Δu are aproximated respectively by the S-wavelenght and the undamped PSD value corresponding to such wavelenght. At a frequency of 1 Hz, assuming for the upper sediments an S-wave velocity of about 200 m/s (see Fig. 2), we obtain shear strain levels of about 10^{-3}% for the events corresponding to the first set of data points in figure 8 (i.e. for lower input levels) while for the second set of data points (i.e. for higher input levels) strain values of the order of 10^{-1}% to 10^{-2}% are obtained. Thus, for these low frequencies, at strain levels of about 10^{-3}% for which we have a soil behaviour that can be considered linear (see Fig. 9) we obtained amplification factors of about 2 while at strain levels of 10^{-1}% to 10^{-2}% for which the soil behaviour becomes strongly non linear, we find larger amplification factors (x 7).

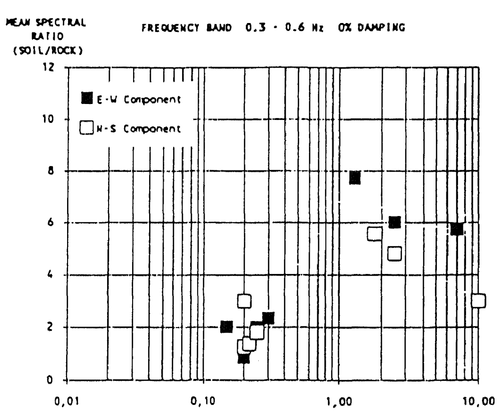

Figure 8. Mean soil/rock spectral ratio versus input motion in rock site (expressed as pseudodisplacement in cm).

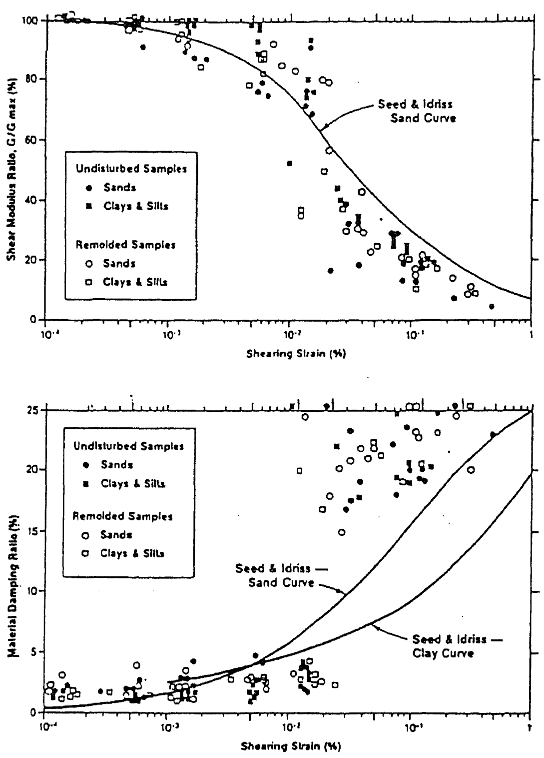

Figure 9. Shear modulus ratio and damping ratio data for Lotung site (from Anderson and Tang, 1987).

5 CONCLUSIONS

Large amplification on soil for low frequencies have been observed in the digital acceleration records obtained in the SMART-1 strong motion array in Taiwan. Analysis of the soil/rock amplification ratios computed from the selected set of accelerograms show a clear dependence of these ratios, for a low frequency range, on the level of the "input" ground motion on rock; the amplification at frequencies lower than 1 Hz are greater for higher input levels, suggesting non-linear behaviour of the soils at the strains involved in these ground motions (10^{-1}% to 10^{-2}% range).

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